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Automated method to distinguish toe walking strides from normal strides in the gait of idiopathic toe walking children from heel accelerometry data

Gita Pendharkar [a,*], Paul Percival [a], David Morgan [a], Daniel Lai [b,1]

[a] Department of Electrical and Computer Systems Engineering, Monash University, Clayton Campus, Melbourne, Australia
[b] School of Engineering and Science, Victoria University, Melbourne, Australia

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ABSTRACT

Toe walking mainly occurs in children due to medical condition or physical injury. When there are no obvious signs of any medical condition or physical injury, a diagnosis of Idiopathic Toe Walking (ITW) is made. ITW children habitually walk on their toes, however can modify their gait and walk with a heel–toe gait if they want to. Correct gait assessment in ITW children therefore becomes difficult. To solve this problem, we have developed an automated way to assess the gait in ITW children using a dual axis accelerometer. Heel acceleration data was recorded from the gait of ITW children using boots embedded with the sensor in the heel and interfaced to a handheld oscilloscope. An innovative signal processing algorithm was developed in IgorPro to distinguish toe walking stride from normal stride using the acceleration data. The algorithm had an accuracy of 98.5%. Based on the statistical analysis of the heel accelerometer data, it can be concluded that the foot angle during mid stance in ITW children tested, varied from 36° to 11.5° while as in normal children the foot stance angle is approximately zero. This algorithm was later implemented in a system (embedded in the heel) which was used remotely to differentiate toe walking stride from normal stride. Although the algorithm classifies toe walking stride from normal stride in ITW children, it can be generalized for other applications such as toe walking in Cerebral Palsy or Acquired Brain Injury subjects. The system can also be used to assess the gait for other applications such as Parkinson's disease by modifying the algorithm.

1. Introduction

Toe walking is a condition in children whereby the child has an abnormal gait and adopts a strong plantar flexed foot position during gait causing them to walk on the head of the metatarsals rather than with a heel–toe gait. Toe walking normally occurs in children with a variety of neurological conditions, however, Idiopathic Toe Walking (ITW) children do not suffer from any neurological problems but still toe walk [1–3]. Idiopathic toe-walkers are diagnosed by excluding all known causes of toe walking including neuromuscular, orthopedic disorders and physical injuries. The severity of toe walking varies from a gait where the children walk with their heels lifted just off the ground and appear to "bounce" as they walk, to a gait where they balance on the tips of their toes as they walk and the heels never contact the ground even when they are standing. The frequency of toe walking in ITW children also varies. Some ITW children walk on their toes 100% of the time, while for others the frequency is variable. Idiopathic toe walking is invariably symmetrical (same in both limbs) in involvement [3].

The problem with ITW is the risk of developing into habitual toe walking. This could lead to a fixed contracture of the Achilles tendon causing ITW children to develop shortened calf muscles [1] which leads to a number of problems. An important effect is that it results in improper balance of the body because the centre of gravity is shifted slightly forward and hence ITW children have a higher risk of falling [2]. This lack of balance also results in lower running speed and frequent injury as the child takes short strides to avoid losing balance. Furthermore during toe walking, most of the load is supported by the bones in the forefoot rather than the heel causing the heel bone to become underdeveloped and cause pain later in life when increased body weight forces the child to walk with heel contact.

Gait assessment of ITW children consists of assessing the severity (how high the heels are from the ground) and extent (frequency) of toe walking. Treatment varies as per the severity. In severe cases of ITW, surgery is recommended, while as in less severe cases orthotics is recommended. In most of the clinics, ITW gait is also assessed by observing and measuring the ankle flexibility rather than toe walking habits [4]. It is also not understood if the calf muscles get shorter with more severe toe

* Corresponding author. Tel.: +61 400579562.
E-mail addresses: gita.mpendharkar@gmail.com (G. Pendharkar), daniel.lai@vu.edu.au (D. Lai).
[1] Tel.: +61 399191044.

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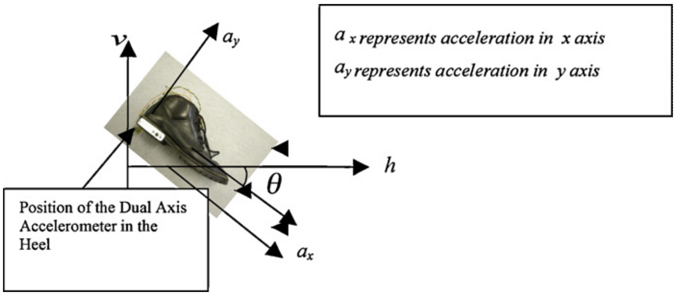

Fig. 1. Boot embedded with a single dual axis accelerometer in the heel.

walking. Following the treatment, boots with graphite plate and eccentric exercises are normally recommended to maintain calf flexibility and a normal heel–toe gait [17].

Unfortunately, assessment of ITW gait in a clinical environment is difficult because the children tend to modify their gait temporarily, especially when they are aware of being observed and monitored by a clinician. It is thus comparatively difficult to obtain an objective measurement of toe walking as ITW children may not toe walk as usual but walk with a heel–toe gait when observed in a gait laboratory [16]. This difficulty motivates our current work in which we propose portable sensor based system for real time assessment of toe walking in ITW children. The system and algorithms were later embedded in the heel of a normal boot (Fig. 1) and used to assess the gait remotely, so that the children (subjects) would not suspect that their gait was monitored.

The algorithm was based on the fact that human walking involves bouts of dynamic and static acceleration. Dynamic acceleration is the acceleration due to rate of change of velocity as the body moves from one position to another. Static acceleration is the acceleration component due to the gravitational component experienced by tilting of the body. Accelerometers have been widely used to estimate the gait cycle characteristics in real time and detect the static and the dynamic activities. Current technological developments have led to the production of inexpensive, unobtrusive, miniature sensors which can be used for ambulatory monitoring and in clinical settings [5]. Accelerometers have been used to estimate normal gait features during walking and for monitoring physical activity [6–9].

In this paper, we have developed an automated way to distinguish a toe walking stride from normal stride in order to assess the gait in ITW children by analyzing the heel accelerometer data using a dual axis accelerometer. The accelerometer was embedded in the heel of the boot and then interfaced to a handheld oscilloscope to record the acceleration signals. An algorithm was developed to distinguish a toe walking stride from a normal stride in a gait cycle [10] using gait parameters (mid stance) obtained from heel accelerometer data. This study was carried out in early 2004 at a clinic in Melbourne. To the best of our knowledge, the ITW gait in children has not been evaluated using heel accelerometer data.

2. Method

2.1. Heel sensor positioning and calibration

The dual axis accelerometer (ADXL202EB $\pm$ 2 g) was placed in the heel of the boot with the x-axis of the accelerometer parallel to the foot in the horizontal surface 'h' and the y-axis being perpendicular to the foot or parallel to the vertical axis 'v' as shown in Fig. 1. This boot was worn by the subject for the gait experiments. The accelerometer was calibrated by performing static trials during which both feet were flat on ground. These values (a_x = 1.94 V and a_y = 2.08 V) were later used as threshold values for toe walking detection in the algorithm.

2.2. Subjects

The study consisted of two groups of ten children (mean age 8 yrs, and mean mass 25 kg) each. The control group consisted of children who were free of any medical conditions such as neurological disorders, spinal injury and walked with a normal heel–toe gait. The ITW did not have any physical and neurological defects, but walked on their toes habitually.

Each child was asked to walk on the treadmill for 2 min in a comfortable walking speed wearing the boots embedded with accelerometers wired to a hand held oscilloscope. It was observed that the normal children had a heel–toe gait while as the ITW children walked in a manner they were comfortable with, which resulted in a toe-walking gait. The two analog output signals (a_x and a_y) of the dual axis accelerometer were recorded on a handheld Fluke oscilloscope while walking. This study had received ethics approval from Monash University and the parents of the children had given informed consent to the work.

2.3. Theory of heel accelerometer data

A gait cycle can be divided into stance (60% duration of a gait cycle) and swing (40%) phases [11]. The stance phase can be further divided into early (heel strike), mid (flat foot) and late (heel up, toes down) stance.

In a normal heel–toe gait, during mid stance, the angle between the foot and ground is zero. However, while toe walking, the foot is inclined to the ground or the horizontal surface 'h' at an angle θ taken as positive toe down as shown in Fig. 1. If an accelerometer is placed in the heel of the boot, the acceleration caused, particularly during mid stance is mainly due to the static acceleration as the dynamic acceleration is negligible [5]. Hence, if the foot (particularly the heel of the boot) is at an angle θ to the ground or the horizontal surface 'h' at an angle θ taken as positive toe down, then as shown in Fig. 1, the equations for a_x and a_y signals can be written in terms of horizontal and vertical accelerations [11].

$$a_x \approx g \sin\theta + a_v \sin\theta + a_h \cos\theta \tag{1}$$

$$a_y \approx -g\cos\theta + a_v\cos\theta + a_h\sin\theta \tag{2}$$

where a_x = acceleration in x-axis; a_y = acceleration in y-axis; a_v = vertical acceleration; a_h = horizontal acceleration; g = gravitational acceleration; θ = angle made by foot with respect to ground position for toe down

However, in a toe walking stride, during mid stance, the heel is at a positive angle θ with respect to ground as shown in Fig. 1. Assuming a_h and a_v to be negligible, Eqs. (1) and (2) can be simplified for mid stance in a toe walking stride as:

$$a_x \approx g \sin\theta \tag{3}$$

$$a_y \approx -g \cos\theta \tag{4}$$

Eqs. (3) and (4) can be solved further to obtain angle θ made by the foot with respect to the ground as follows:

$$\theta = \tan^{-1}\left(\frac{-a_x}{a_y}\right) \tag{5}$$

In a normal stride, the foot remains flat (stationary) on the ground during mid stance. As the angle of inclination of the foot with respect to ground, θ = 0, Eqs. (3) and (4) for mid stance in normal stride can be simplified as:

$$a_x \approx 0 \tag{6}$$

$$a_y = -g \tag{7}$$